

Biomedical Applications of Electroactive Polymers

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Abstract

We are investigating applications of mechanically electroactive polymers (EAPs), with the intent of applying them to design of new and improved medical devices. Our initial emphasis in this work is on blood pumps and robotic instruments for minimally invasive surgery. In blood pumps, EAPs have potential to permit design of more tightly integrated and biomimetic devices. In surgical instruments, the flexibility and high energy density of EAPs have potential for enabling replacement of limited dexterity mechanically actuated instruments with electronically mediated instruments having multiple degree of freedom effectors. This paper provides an overview of our efforts to date with field-activated ferroelectrics and dielectric elastomers.

Introduction

Electroactive polymers are notable for providing large actuation strains and energy densities while retaining flexibility and toughness [1, 2]. While typically the mechanical characteristics that EAPs share with natural muscle are limited to strains and energy densities and do not extend to viscoelastic or activation properties, they may be capable of playing roles analogous to natural muscle in a variety of applications.

For blood pumps, EAPs may permit the design of tightly integrated biomimetic devices. A typical implantable blood pump, developed at our institution and presently in clinical use [3] is illustrated in Figure 1. This is a positive displacement design, meant to provide a blood pulse similar to that provided by the natural heart. As is typical of devices of its kind, the blood pump section comprises a rigid case and a polymeric sac or lining. A separable electromechanical energy converter alternately compresses the polymer sac and reverses to permit it to re-fill. The device has a fixed volume beyond which it cannot accept additional blood during its filling phase. This has implications in the device's ability to accommodate changes in blood pressures and therefore for the control of the device.

The natural ventricle is a muscular chamber, the motions of whose walls provide pulsatile or cyclic pumping. While the ventricle certainly contains specialized micro- and macro-structures (most notably the blood supply, electrical conduction system, some connective tissue and a specific organization of muscle fibers), it still takes the general form of a contractile chamber. This is in contrast with the typical engineered design, which makes use of a passive chamber, a separate actuator, and rigid structural housings that serve no other purpose. While biology's solutions to problems should not be prescriptive of our solutions, largely due to our access to different materials and our lack of evolutionary constraints, the potential for construction of moving-wall pumps is attractive because of their potential to be compact and to avoid limitations such as fixed filling volumes.

Minimally invasive surgery (MIS) involves manipulation of tissues through small skin portals (typically three to ten millimeters) rather than through the large incisions used in "open" surgical procedures. MIS can provide for more rapid recovery, especially with regard to return to full activity, reduced intensity of postoperative care, reduced cosmetic impact, and higher patient satisfaction. Currently, MIS procedures are performed largely with long-handled versions of standard surgical instruments. Most instruments have no more than one effector degree of freedom (e.g., grasping, cutting) and are difficult to manipulated because of the restrictions imposed by the fulcrum at the skin site, the rigid straight shaft, and surrounding structures.

One potential means for enabling more complex MIS procedures

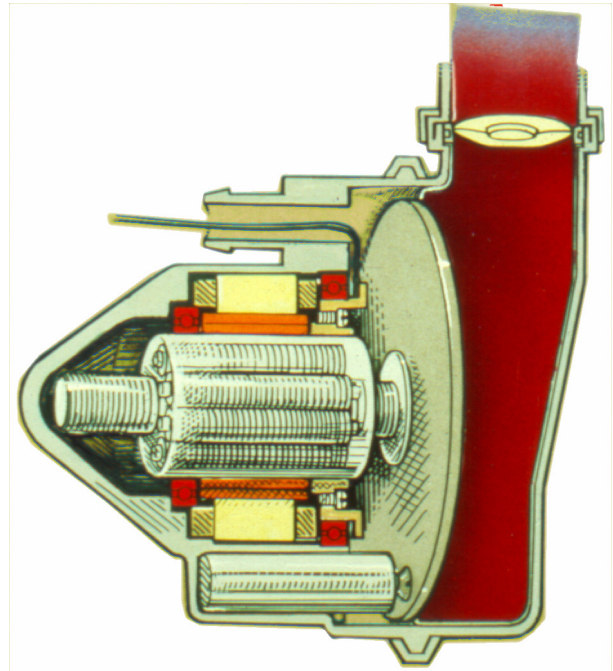


Figure 1. A ventricular assist device (univentricular blood pump) developed at our institution. The electromechanical energy converter on the left alternately compresses and permits re-filling of the polymeric sac that lines the blood pump housing on the right.

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or easing the performance of existing procedures is the development of multiple degree-of-freedom instruments. These might perform multiple functions such as cutting and grasping [4] or might provide complex articulations of the instrument tip. By putting actuating materials at or close to the instrument tip, EAPs might eliminate complex arrangements of push rods or tendon wires that would otherwise be needed to control multiple-function or multiple degree of freedom devices.

We have limited our investigations to field-activated EAPs due to their high energy densities, dry operation and fabrication options. Specifically, a number of investigators have studied behavior of these materials and have designed various actuators that effectively capture activation strains [e.g., 5]. We have chosen an analytical approach in which a combination of testing and analysis provides us with models of material behavior which can then be used to inform device design. Herein, we report on early studies of diaphragmatic actuators for use in pumps and linear actuators for use in robotics.

Diaphragmatic actuators

Experimental work with diaphragmatic actuators is reported more fully [6] and theoretical work is reported in [7]. Experimental results reported in [6] are abstracted here. We tested pressure-volume characteristics of circular dielectric elastomer diaphragms in order to predict their behavior in a pump such as the hypothetical design depicted in Figure 2.

Films of polyacrylate tape (3M VHB 4905 or VHB 4910) were used as received. Silicone rubber films of 90 micron nominal thickness (NuSil CF19-2186) were prepared by spin casting on polystyrene culture dishes. Polyacrylate films were subjected to large biaxial pre-strains in a frame-like fixture as has been shown to be necessary for them to withstand large electric fields and attain high energy densities. Silicone films were subjected to smaller or no pre-strain. The films were mounted to a disc-shaped fixture having a 3.8 cm diameter circular opening, both surfaces coated with carbon-filled silicone grease, and composite carbon-filled acrylic and copper tape leads were applied. The fixture was mounted to a chamber and a simple U-tube manometer was used to apply pressure to the chamber and measure volume displacement of the diaphragm. An air space was maintained between the manometer fluid and the chamber so that any effect of liquids upon the grease electrode could be avoided.

Electric fields were applied using a Trek model 610D high-voltage supply. Field strengths were determined by the voltage and the stretched film thickness, estimated assuming incompressibility. Data are reported using the estimated field applied to the flat films. Diaphragm displacement would have caused significant thinning of the films and the applied fields therefore increased with volume displacement. At each applied voltage, the diaphragm pressure was increased in small increments until the diaphragm was roughly hemispheric. Voltages were increased in modest increments until electrical failure occurred. Polyacrylate films tended to show large tears at failure, while silicone films showed pinhole leaks and electrical shorting.

Highly pre-stained (400% x 200%) polyacrylate films were found to have linear pressure-volume (PV) characteristics (Figure 3, upper panel). The slope of the PV characteristic, or elastance, and its inverse, the diaphragm compliance, were found to vary systematically with applied field. At slightly lower pre-strain (300% x 150 %), the polyacrylate films had modestly nonlinear characteristics, with compliance increasing at larger volumes (Figure 3, lower panel). The overall shape of the passive PV characteristic is a composite of changing radius of curvature, diaphragm thinning and dependence of elastic modulus upon strain. When activated, electric field strengths also increase with diaphragm thinning. We expect that the linear characteristic occurs when certain competing effects of polymer strain exactly cancel.

Silicone films having no pre-stretch exhibited nearly constant compliance but with a marked rightward shift of the PV characteristic as the electric field was applied (Figure 4, upper panel). In contrast, moderately pre-stained silicone films (Figure 4, lower panel) showed a variable compliance similar to that of the polyacrylate.

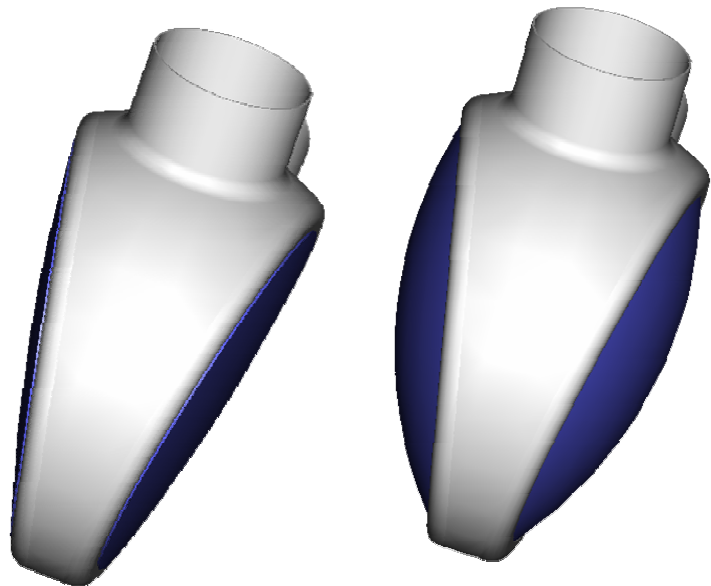


Figure 2. A hypothetical blood pump using electroactive polymers. The design retains the supporting housing (gray) used in present designs but uses EAP diaphragms to impart pumping action.

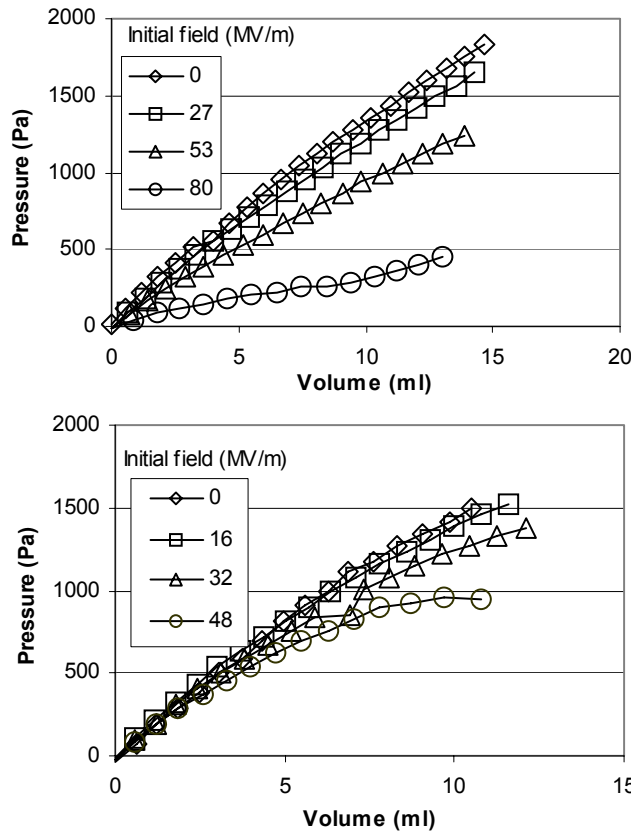


Figure 3. Pressure-volume responses of a circular polyacrylate films pre-strained at 400x200% (top) and 300x150% (bottom), under varying electric

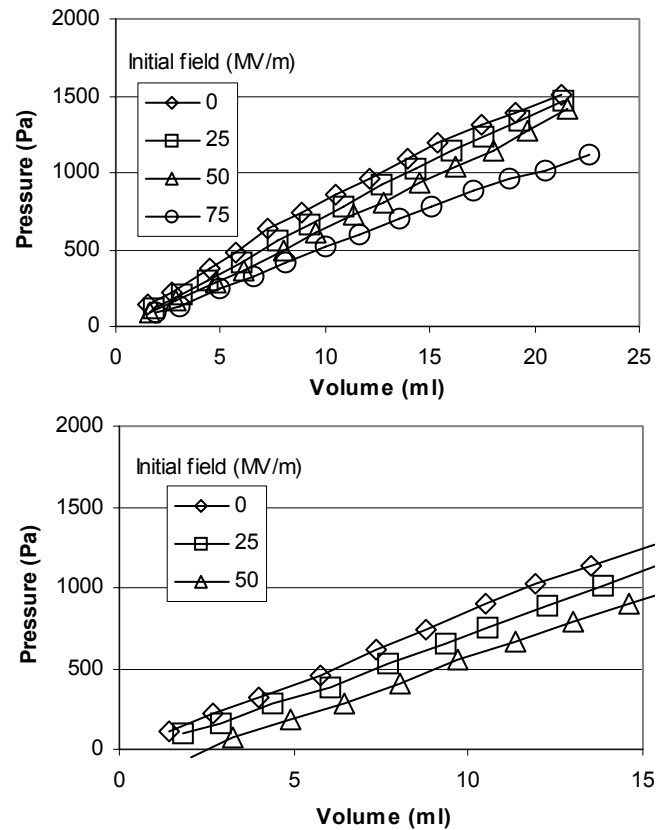


Figure 4. Pressure-volume responses of a circular silicone rubber films pre-strained at 25x25% (top) and without pre-strain (bottom), under varying electric fields.

Shifts in the PV characteristics that occur with field activation allow us to posit pressure-volume work loops for hypothetical valved pumps. In all cases (e.g., Figure 5), work loops and volume displacements were largest when the outlet pressure was only infinitesimally larger than the inlet pressure, though positive work output could be obtained under other conditions. From the largest identifiable work loops, we can compute an energy density for the active materials. At the highest fields shown in Figures 3 and 4, energy densities were 240 mJ/cc for the polyacrylate and 29 mJ/cc for the silicone. These figures for work loops are lower than are those previously reported [1] for single elastic recoil strokes.

Linear actuators

Work on testing of linear actuators is reported in [8] and abstracted here. We prepared fifteen micron films of poly(vinylidene fluoride-trifluoroethylene) (p(VDF-TrFE)) and pre-strained, annealed and irradiated the films as described in [2]. Films were sputter-coated with 40 nm gold electrodes on both sides, folded to isolate one electrode, and rolled into tubes of approximately 0.3 cm diameter and 3.0 cm length. Leads were applied to the inner electrode, which was exposed at one end by the manner of folding, and to the outer electrode, using silver-filled epoxy.

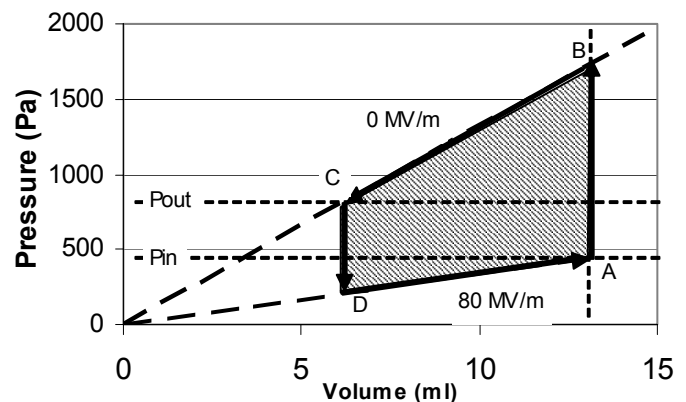


Figure 5. Example of a hypothetical pressure-volume work loop, constructed by assuming pump inlet and outlet pressure P_{in} and P_{out} and positing the presence of perfect one-way valves at the inlet and outlet of the chamber. The PV characteristics are from Figure 3 for the 400x200% pre-strain polyacrylate film.

The resultant strip actuators, which were either left in tubular form or flattened into a ribbon shape, were mounted vertically between a fixed portion of the test stand and a linear slide. Weights could be applied to the slide to load the strip. Slide movements were recorded by an LVDT. Time-varying strains in response to both changes in loading and field activation were recorded. Loading was limited to that which provided a one percent strain. The applied field was limited to approximately 100 MV/m. When strip actuators failed, it was typically by delamination of the gold electrodes, characterized by loss of actuator capacitance without an increase in conductivity across the film.

Recording of responses to step changes in load revealed significant viscoelasticity; the model of Figure 6 accounted for most of the material's response. By providing sufficient time at constant load to complete most of the response to a load change before activating the material, responses to electric field activation could be separated from the response to loading. Typical activation responses (Figure 7) were more rapid than the response to loading but still showed significant lag. In that the reported frequency response of p(VDF-TrFE) is quite good [9]. The inclusion of significant amounts of un-electroded material in the rolled structure (up to 20% of the cross-section) is likely to explain the discrepancy. Similarly, both the un-electroded material and the thin but stiff gold electrodes are likely to explain the 2 % strain that was obtained under field conditions that would be expected to elicit 2.5% or larger strains in the unconstrained copolymer.

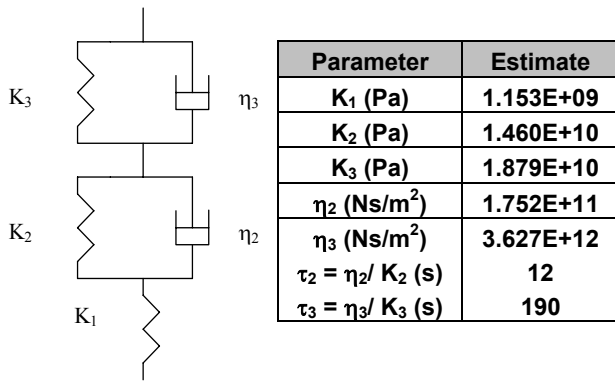


Figure 6. Viscoelastic model of the passive response of electroactive p(VDF-TrFE) to step changes in load. Model parameters are normalized per unit cross-sectional area and length.

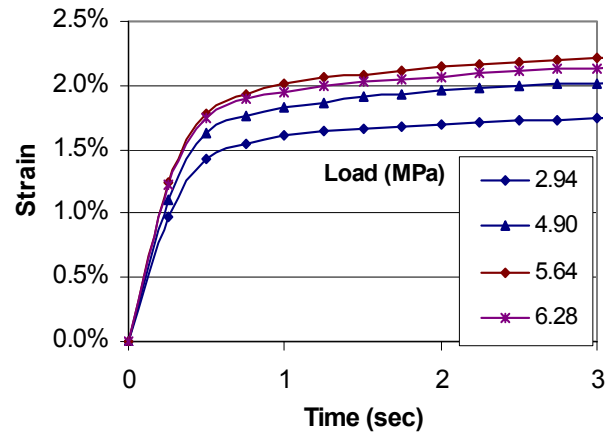


Figure 7. Strain responses of p(VDF-TrFE) strip actuators to activation at 92.5 MV/m, under different loading conditions.

Prospects for practical devices

The field-variable compliance behavior of the diaphragm actuators is intriguing because the natural ventricle is often modeled simply as a variable compliance. While the natural ventricle's compliance varies by two orders of magnitude in its transition from diastole (filling) to systole (ejection), a compliance ratio of only about four to one was demonstrated here, for the polyacrylate. If one posits the use of a sufficient number of layers so that the un-activated diaphragm is sufficiently stiff to eject fluid against normal arterial pressures, it would be too stiff to accept fluid in its activated state at naturally-occurring inlet pressures during pump filling. Significant improvements in the materials will be required if ventricular behavior is to be mimicked using simple circular diaphragms. On the other hand, constructs may be developed that would provide for a simple, compact and useful pump, even if fails, as to current devices, to replicate all of the properties of the natural organ. While the un-stretched silicone films withstood lower fields and provided lower cyclic energy densities, a device designer might take advantage of their volume shift characteristics for use in pumps, like blood pumps, that need to operate at very low inlet pressures.

It is quite likely that simple geometric forms such as circular diaphragms can be used in the design of pumps having a suitable shape and size, but ideal designs may require more complex shapes. This work will need to be driven by analysis rather than experimentation, most likely using finite element analysis adapted to efficiently studying the mechanics of thin films. The work described in [7] is a start in that direction.

Practical problems relating to both ordinary mechanical properties and electroactive properties of the active materials need also to be addressed. While there have been anecdotal reports of very good durability in EAP actuators, and no innate wear-out mechanisms have been reported for field-activated materials, failure mechanisms have not been carefully studied and the practical durability of the present materials is unknown.

The need for high voltages is an obvious but not necessarily critical concern. The use of high voltages means that peak power supply currents can be quite low, and with low current capability safety becomes much less of a concern. On the other

hand, distribution of high voltages is complicated by insulation requirements, and methods for highly localized voltage step-up may therefore be useful. The polyacrylate and silicone materials described here do not have unusually high dielectric constants; they get their good energy densities from their high dielectric strength (elastic energy density is proportional to the dielectric constant and to the square of the applied field [1]). Work by our group to develop high dielectric constant elastomers [10] is aimed at permitting marked reductions in working voltages.

The rolled film linear actuators were stiffened by their geometry and their active responses were diminished by their metal electrodes and the inclusion of un-electroded material in the actuator cross-section. The copolymer's slow passive viscoelastic response may be problematic in some applications. Clearly, improved actuator forms and alternative electrode systems (e.g., [11]) are needed.

Much of the work to date in EAPs had been done with "found" materials rather than materials developed explicitly to be electroactive. This is changing with the development of high dielectric elastomers and other materials whose composition and structure are dictated by their intended electroactivity. It is important to note that materials that have typically been developed as dielectrics - electrical insulators - need to have high dielectric strength and usually have high stiffness so that physical movement in capacitors and conductor pairs is minimal. In dielectric elastomers, we are looking for good dielectric strength in soft, preferably incompressible, materials capable of undergoing large elastic deformations. It is no surprise that such materials are relatively uncommon; this does not indicate that they cannot be developed.

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